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Revisiting the 'enigma' of musicians with dyslexia: auditory sequencing and speech abilities

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Abstract

Previous research has suggested a link between musical training and auditory processing skills. Musicians have shown enhanced perception of auditory features critical to both music and speech, suggesting that this link extends beyond basic auditory processing. It remains unclear to what extent musicians who also have dyslexia show these specialized abilities, considering often-observed persistent deficits that coincide with reading impairments. The present study evaluated auditory sequencing and speech discrimination in 52 adults comprised of musicians with dyslexia, nonmusicians with dyslexia, and typical musicians. An auditory sequencing task measuring perceptual acuity for tone sequences of increasing length was administered. Furthermore, subjects were asked to discriminate synthesized syllable continua varying in acoustic components of speech necessary for intra-phonemic discrimination, which included spectral (formant frequency) and temporal (voice onset time (VOT) and amplitude envelope) features. Results indicate that musicians with dyslexia did not significantly differ from typical musicians and performed better than nonmusicians with dyslexia for auditory sequencing as well as discrimination of spectral and VOT cues within syllable continua. However, typical musicians demonstrated superior performance relative to both groups with dyslexia for discrimination of syllables varying in amplitude information. These findings suggest a distinct profile of speech processing abilities in musicians with dyslexia, with specific weaknesses in discerning amplitude cues within speech. Since these difficulties seem to remain persistent in adults with dyslexia despite musical training, this study only partly supports the potential for musical training to enhance the auditory processing skills known to be crucial for literacy in individuals with dyslexia.

Keywords: dyslexia, music, auditory, speech, children

Learning to read is essential for academic and vocational success, yet approximately 5-17% of the population significantly struggles to read and comprehend text because of a specific learning disorder known as dyslexia (Lyon, 2003; Peterson & Pennington, 2012; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Dyslexia is characterized by difficulties specific to reading that cannot be explained by hearing difficulty, cognitive deficits, lack of motivation, or inadequate educational opportunities. Moreover, these difficulties typically persist into adulthood (McLoughlin, Leather, & Stringer, 2002). Delineating the underlying mechanisms that give rise to dyslexia has proven to be an ongoing challenge, as reading is a complex process. It has been suggested that dyslexia is unlikely to manifest as a singular deficit and instead may arise from multiple risk factors (Ozernov-Palchik, Yu, Wang, & Gaab, 2016; Pennington, 2006; van Bergen, van der Leij, & de Jong, 2014). Some of the key deficits associated with dyslexia include poor phonological awareness (the ability to manipulate speech sounds within words (Lyon, 2003; Ramus, 2001, 2004; Snowling, 2000)), weaknesses with phonological working memory (Ramus & Szenkovits, 2008), and difficulty with rapid automatized naming (Wagner & Torgesen, 1987; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). Therefore, the multiple deficit view of dyslexia brings forth consideration of additional factors that may contribute to this disorder.

Learning to read also relies on nuanced perception and manipulation of speech sounds and mapping them to a written, symbolic code (Flax, Realpe-Bonilla, Roesler, Choudhury, & Benasich, 2009; Nation & Hulme, 1997; Pennington & Lefly, 2001; Snowling, Gallagher, & Frith, 2003). Accordingly, deficient speech sound perception has been observed in some individuals with dyslexia (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Liberman, 1985; Manis et al., 1997; Mody, Studdert-Kennedy, & Brady, 1997; Vandermosten et al., 2010; Vandermosten et al., 2011). Considerable evidence suggests that deficits in the perception of basic auditory cues may underlie these speech perception difficulties (as reviewed in (Hamalainen, Salminen, & Leppanen, 2013)). Therefore, research

has proposed a strong link between early auditory processing, phonological awareness, and subsequent literacy skills (Tallal, 2004).

Yet, it is puzzling that trained musicians, known to have specialized auditory processing skills (Kraus & Chandrasekaran, 2010; Zatorre, Chen, & Penhune, 2007), can also have persistent dyslexia (Bishop-Liebler, Welch, Huss, Thomson, & Goswami, 2014). This 'enigma' of musicians with dyslexia, coined by Weiss and colleagues (2014), calls into question the extent of a direct link between basic auditory processing and literacy skills in all individuals with dyslexia. Therefore, investigation of musicians with dyslexia may serve as one pathway to further investigate the multiple deficit model through the lens of musical training, considering multiple risk factors and a complex interplay between perceptual and cognitive mechanisms that may give rise to dyslexia (Pennington, 2006).

Although a putative association has been established between basic auditory processing difficulties early on in development and subsequent dyslexia, the specific nature of this link remains unclear (Hamalainen et al., 2013). Weaknesses in basic auditory processing have been reported in individuals with dyslexia for contexts which include discrimination of pitch and frequency modulation in quiet and in noise (Ahissar, Protopapas, Reid, & Merzenich, 2000; Amitay, Ahissar, & Nelken, 2002; Lorusso, Cantiani, & Molteni, 2014; Tallal & Piercy, 1973; Wright & Conlon, 2009), and even voice recognition (Perrachione, Del Tufo, & Gabrieli, 2011). These difficulties have been suggested to manifest from a general impairment in stimulus-specific prediction, meaning that individuals with dyslexia exhibit difficulty forming perceptual anchors, which typically allow for increased efficiency and accuracy with subsequent repetitions of a given stimulus (Ahissar, Lubin, Putter-Katz, & Banai, 2006; Oganian & Ahissar, 2012). Within this area of inquiry, one prominent avenue of investigation is that of non-linguistic temporal processing (Tallal, 2004). Numerous studies have found that children with language and literacy deficits have difficulties with discriminating sounds that differ by rapid temporal changes (Tallal & Piercy, 1973, 1974; Tallal, Stark, & Mellits, 1985). Furthermore, temporal discrimination abilities of infants at seven months of age have been shown to predict language outcomes at age three (Benasich,

2002), and in turn these abilities in early primary school years have been shown to predict subsequent literacy skills (Steinbrink, Zimmer, Lachmann, Dirichs, & Kammer, 2014b).

Alternative evidence has indicated that temporal processing difficulties in dyslexia are specific to perception of the amplitude rise time and slow-rate modulations captured by the amplitude envelope (Goswami et al., 2002; Lorenzi, Dumont, & Fullgrabe, 2000; Rocheron, Lorenzi, Fullgrabe, & Dumont, 2002; Talcott et al., 2000), critical cues for speech discrimination that convey amplitude changes over time and are known to signify the rhythmic patterns of speech (Cutler, 1994; Rosen, 1992). Furthermore, temporal processing deficits in dyslexia have been shown in music-specific contexts, as some children with dyslexia have demonstrated weaknesses with beat synchronization, rhythm copying, and rhythmic entrainment (Leong & Goswami, 2014a, 2014b; Overy, Nicolson, Fawcett, & Clarke, 2003; Thomson, Fryer, Maltby, & Goswami, 2006; Thomson & Goswami, 2008; Wolff, 2002) as well as discrimination of meter (i.e., the discrimination of beat frequency and musical accent within rhythmic phrases (Huss, Verney, Fosker, Mead, & Goswami, 2011)).

In addition, basic auditory training has led to improved language and reading abilities in children and adults with dyslexia (Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Temple et al., 2003). Although these studies demonstrate the potential for basic auditory training to benefit literacy development, further research has importantly revealed that not all individuals with dyslexia show deficits in auditory processing (Christmann, Lachmann, & Steinbrink, 2015; Grube, Cooper, Kumar, Kelly, & Griffiths, 2014; Marshall, Snowling, & Bailey, 2001; Nitttrouer, 1999; Ramus, 2003; Rosen, 2003; Steinbrink, Klatte, & Lachmann, 2014a). Indeed, considerable variability has been found in auditory, speech and phonological processing skills within individuals with dyslexia (Heath, Hogben, & Clark, 1999; Law, Vandermosten, Ghesquiere, & Wouters, 2014). In light of these equivocal findings, it is particularly intriguing to consider what can be learned about the nature of this relationship from musicians with dyslexia, as these individuals seem to demonstrate reading difficulties despite specialized auditory skills in the musical domain.

Musical training has been put forth as a promising tool to promote auditory specialization and therefore support literacy skill development (Rolka & Silverman, 2015; Tallal & Gaab, 2006). Individuals with musical training have demonstrated heightened discrimination skills over non-musicians for several components of auditory processing, including spectral features such as pitch (Amir, Amir, & Kishon-Rabin, 2003; Besson, Schon, Moreno, Santos, & Magne, 2007; Carey et al., 2015; Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Koelsch, Schroger, & Tervaniemi, 1999; Magne, Schon, & Besson, 2006; Micheyl, Delhommeau, Perrot, & Oxenham, 2006; Spiegel & Watson, 1984), and temporal features such as elements of timing (Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2012; Ehrle & Samson, 2005; Gaab et al., 2005; Rammsayer & Altenmüller, 2006).

These pitch and timing cues are not only necessary for music but are also critical to speech processing, which demands precise perception of the formant frequencies that characterize vowels and consonants within a specific, rapid temporal framework (Stevens, 1980). Overlapping spectral and temporal features across music and speech perception suggest that the auditory specialization achieved through intensive musical training may also be associated with advantageous speech processing abilities (Chandrasekaran & Kraus, 2010; Chobert, Francois, Velay, & Besson, 2012; Parbery-Clark, Skoe, & Kraus, 2009; Patel, 2011, 2012). Accordingly, trained musicians have shown superior detection of spectral features within speech compared to non-musicians (Deguchi et al., 2012; Schon, Magne, & Besson, 2004; Thompson, Schellenberg, & Husain, 2003), as well as heightened perception of temporal speech-specific features for properties such as segmental structure (Francois, Chobert, Besson, & Schon, 2012; Moreno et al., 2009) and the amplitude envelope (Zuk et al., 2013b). In addition, specialized electroencephalographic and auditory brainstem responses during sound discrimination have been reported in musicians over non-musicians for music and speech stimuli characterized by differences in frequency, duration, and intensity (Jentschke, Koelsch, & Friederici, 2005; Moreno & Besson, 2006; Tervaniemi et al., 2009; Weiss & Bidelman, 2015; Wong, Skoe, Russo, Dees, & Kraus, 2007). Furthermore, longitudinal studies have shown changes in these neural responses to speech following musical intervention in childhood (Habibi, Cahn, Damasio, & Damasio, 2016; Kraus, Hornickel, Strait,

Slater, & Thompson, 2014a; Kraus et al., 2014b, 2014c). These specialized neural responses to speech in adults with musical training have also been shown to significantly relate to the total amount and intensity of musical training (Musacchia, Strait, & Kraus, 2008), suggesting that long-term dedication to musical training that involves intense practice routines may facilitate distinct mechanisms for speech processing. Thus, a growing body of evidence supports the notion that musical training may serve as an effective outlet to advance basic auditory and speech-specific processing skills, which in turn may positively impact reading skills (Tallal & Gaab, 2006).

Musicianship has furthermore been directly linked with early and developing language and literacy skills (Fisher & McDonald, 2001; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2012; Williams, Barrett, Welch, Abad, & Broughton, 2015). Musical training as well as musical aptitude (as indicated by music perception tasks) have shown positive associations with phonological abilities such as rhyming, blending, sound isolation, and segmentation (Anvari, Trainor, Woodside, & Levy, 2002; Forgeard, Schlaug, Norton, Rosam, & Iyengar, 2008; Loui, Kroog, Zuk, Winner, & Schlaug, 2011; Standley & Hughes, 1997; Zuk, Andrade, Andrade, Gardiner, & Gaab, 2013a). Moreover, music-based intervention has resulted in improved phonological processing and speech segmentation in typically developing school-age children as well as struggling readers (Bhide, Power, & Goswami, 2013; Dege & Schwarzer, 2011; Hurwitz, Wolff, Bortnick, & Kokas, 1975; Moreno et al., 2009; Overy, 2003; Przbylski et al., 2013; Santos, Joly-Pottuz, Moreno, Habib, & Besson, 2007; Thomson, Leong, & Goswami, 2013).

Positive relationships have also been found between musical skill and various reading abilities including reading speed and accuracy (Barwick, Valentine, West, & Wilding, 1989; Corrigall & Trainor, 2011; Douglas & Willatts, 1994; Gardiner, Fox, Knowles, & Jeffrey, 1996; Goswami, Huss, Mead, Fosker, & Verney, 2012; Hurwitz et al., 1975; Lamb & Gregory, 1993; Register, Darrow, Standley, & Swedberg, 2007; Standley & Hughes, 1997; Strait, Hornickel, & Kraus, 2011; Zuk et al., 2013a). In addition, music-based interventions in children with dyslexia have shown improvements in phonological awareness (Atterbury, 1985; Farmer, Kittner, Rae, Bartko, & Regier, 1995; Flaunacco et al., 2015; Habib et al., 2016; Overy, 2003; Santos et al., 2007; Thomson et al., 2013), spelling (Atterbury, 1985;

Farmer et al., 1995; Overy, 2003; Santos et al., 2007), and reading skills (Flaugnacco et al., 2015; Habib et al., 2016; Thomson et al., 2013). However, the extent of these gains warrants further investigation as the only study to include multiple control groups found no significant differences in improvements between children who received six weeks of computer-based rhythm training and others who received a traditional language-based intervention, even compared to controls who did not engage in any specific training (Thomson et al., 2013). Thus, although a connection between music and literacy is evident, the nature of this relationship has yet to be sufficiently specified.

Despite the collective evidence linking auditory processing deficits with reading difficulties and the potential to remediate these skills through musical training, there are numerous cases of individuals with dyslexia with persistent difficulties who study classical music at the highest levels and become professional musicians (Bishop-Liebler et al., 2014). Thus, this population raises significant questions as to whether individuals with dyslexia who have received extensive musical training evidence specific advantages in auditory processing relative to those with dyslexia who have not had musical training. If so, questions remain as to why these individuals still develop (persistent) literacy difficulties, and to what extent their putative advantages in auditory processing reflect a direct influence of musical training or rather an early propensity for specialized auditory processing.

To date, only two studies have investigated auditory processing skills in musicians with dyslexia. The first study to examine this compared musicians with dyslexia to typical musicians on a wide variety of auditory processing abilities, including non-linguistic spectral and temporal discrimination, speech sound perception in noise, synchronous finger tapping, and auditory verbal and non-verbal working memory (Weiss, Granot, & Ahissar, 2014). Musicians with dyslexia performed comparably with typical musicians on all of the basic auditory processing and finger tapping tasks. Yet, musicians with dyslexia demonstrated poor auditory working memory performance relative to typical musicians for phonological and musical stimuli, thus contributing to the body of literature that attributes poor working memory to be a critical deficit underlying dyslexia (de Jong, 1998; Wagner & Torgesen, 1987).

The second investigation of musicians with dyslexia to date also identified no significant differences in auditory processing skills between this population and typical musicians, as measured by discrimination tasks of frequency, intensity, the amplitude rise time conveyed by the amplitude envelope, and rhythm perception (Bishop-Liebler et al., 2014). Additionally, musicians with dyslexia performed better than non-musicians with dyslexia on the majority of these measures, but did not demonstrate a significant advantage on amplitude rise time perception or the duration discrimination task. Thus, extant findings suggest that musicians with dyslexia exhibit specialized auditory processing skills similar to typical musicians for certain auditory constituents but not all, which is conceivable since the difficulties associated with dyslexia typically continue into adulthood (McLoughlin et al., 2002). Yet, it remains unclear whether musicians with dyslexia also exhibit specific deficits with speech processing as previously shown in individuals with dyslexia (Bogliotti et al., 2008; Liberman, 1985; Manis et al., 1997; Mody et al., 1997; Vandermosten et al., 2010; Vandermosten et al., 2011).

As reviewed above, investigations of musicians with dyslexia have primarily focused on specific components of auditory processing, and characterization of speech-specific processing abilities remain largely unspecified. Further investigation of the abilities of musicians with dyslexia for non-speech and speech-specific perception tasks has the potential to provide further insight on the extent of the ‘musician advantage’ this unique population possesses, and the auditory expertise that may be observable despite persistent reading difficulties. As such, the lack of differences in auditory processing abilities in musicians with dyslexia relative to typical musicians brings forth a question of whether these ‘auditory advantages’ extend to speech-specific contexts. Research evidence has yet to uncover whether the superior speech-specific processing abilities shown in typical musicians in the spectral (Deguchi et al., 2012; Magne et al., 2006; Schon et al., 2004; Thompson et al., 2003) and temporal (Francois et al., 2012; Moreno et al., 2009; Zuk et al., 2013b) domains may also be evident within musicians with dyslexia. Furthermore, prior evidence has suggested weaknesses in auditory working memory in musicians with dyslexia compared to musicians without (Weiss et al., 2014). Accordingly, it is unclear whether musicians with dyslexia may be characterized by working memory deficits in general, or whether the auditory

expertise afforded by musical training may be associated with some advantages in processing auditory information even when taxing the working memory system. Auditory sequencing is particularly of interest since attending to and reproducing auditory sequences is one of the primary auditory skills developed through musical training (Carey et al., 2015; Loui, Wessel, & Hudson Kam, 2010; Rohrmeier, Rebuschat, & Cross, 2011; van Zuijen, Sussman, Winkler, Naatanen, & Tervaniemi, 2005). Moreover, auditory sequencing has also been shown to be a critical building block for language (Tallal & Gaab, 2006; Tallal et al., 1985). To date, auditory sequencing abilities have yet to be investigated in musicians with dyslexia.

The present study will advance the extant indicators of auditory processing abilities in musicians with dyslexia through a battery of tasks measuring non-speech and speech-specific auditory processing. As with previous investigations of musicians with dyslexia, this study precludes determination of whether the putative specialization in musicians with dyslexia may be the direct result of long-term musical training, or instead a predisposition for musical achievement. Even so, the present study will further characterize auditory processing abilities in musicians with dyslexia through tasks that have not yet been utilized to assess musicians with dyslexia. These tasks include (i) an auditory processing task measuring tone sequencing skills and (ii) speech-specific perceptual tasks that have been previously employed to explore processing abilities in musicians (Zuk et al., 2013b). Specifically, these speech tasks measure discrimination thresholds of synthetic syllable continua that vary in spectral (frequency) and temporal (amplitude envelope and voice onset time) features. Performance in musicians with dyslexia will be directly compared with that of typical musicians, as well as non-musicians with dyslexia.

Consequently, we identified two hypotheses. First, we expected to find no significant differences in accuracy on the tone-sequencing task between musicians with dyslexia and typical musicians, consistent with prior findings of no significant differences between these groups for auditory processing tasks (Bishop-Liebler et al., 2014; Weiss et al., 2014). By comparison, nonmusicians with dyslexia were hypothesized to show significantly poorer performance relative to the groups with musical training. Yet, we also anticipated that musicians with dyslexia may reveal slower reaction times than typical musicians

for the tone sequencing task, based on the evidence of weaknesses in speed of processing of individuals with dyslexia (Breznitz & Misra, 2003; Catts, Gillispie, Leonard, Kail, & Miller, 2002). The second hypothesis was for the speech-specific tasks that a certain degree of specialization would be evident in musicians with dyslexia, since we expected that the reported advantages in auditory processing in this group would extend to speech-specific contexts as well. Yet, musicians with dyslexia were hypothesized to perform more similarly to nonmusicians with dyslexia for the discrimination of syllable continua requiring distinction of temporal features of speech, considering the significant evidence for deficits in dyslexia in discerning temporal information (Goswami et al., 2002; Lorenzi et al., 2000; Rocheron et al., 2002; Talcott et al., 2000; Vandermosten et al., 2010; Vandermosten et al., 2011). In particular, these groups were expected to perform comparably for discrimination of syllables that vary in amplitude envelope cues with superior performance in typical musicians, based on prior evidence of similar performance between musicians and nonmusicians with dyslexia for detection of amplitude rise time cues in a non-speech context (Bishop-Liebler et al., 2014). Thus, the present investigation sought to characterize specialized auditory sequencing and speech processing skills and identify whether persistent weaknesses were evident in musically trained individuals with dyslexia. Furthermore, the present study sought to uncover the extent of an association between musical training and specific aspects of auditory processing critical to early literacy development. Taken together, these aims may provide implications for the potential of musical training to benefit auditory and literacy skill development in individuals with dyslexia.

Methods

Participant Demographics

Fifty-two healthy, monolingual, native British English-speaking adults were included in the present study (17 male, 35 female, ages 18-36 years with mean age: 20.89 yrs, SD: 2.82). Three groups classified participants as follows: typical musicians (TYPMUS; $n = 17$, 14 female, mean age: 21 yrs, STD: 1.73), musicians with dyslexia (DYSMUS; $n = 19$, 8 female, mean age: 20.68 yrs, STD: 2.29), and nonmusicians with dyslexia (DYSNonMUS; $n = 16$, 13 female, mean age: 21.06 yrs, STD: 4.17). All

participants were UK university students or recent graduates, recruited through student service departments, music departments, or academic departmental postings at their institutions. All participants with dyslexia had previously received a formal diagnosis from an educational psychologist or qualified specialist. Formal diagnosis of dyslexia among participants adhered to UK definitions of dyslexia and evaluation protocols, as described by the Department of Education and Schools Guidelines (DfES, 2005). The age of dyslexia diagnosis in these participants ranged from childhood to adulthood (mean age: 17.63 years, SD: 3.85, with no significant differences in musician vs. nonmusician groups, though three participants did not provide this information). Musicians (TYPMUS and DYSMUS) in this study were defined as either being enrolled in or having obtained a music performance degree specializing in classical or jazz music (see Table 1 for details of musical training). On average, musicians in both groups began studying music at a mean age of seven years and had completed approximately thirteen years of musical training (as shown in Table 1 by group). DYSNonMUS had no prior musical training outside of the requirements of the general music curriculum in school. Participants were confirmed to have no neurological abnormalities, hearing impairments, nor additional neuropsychological or developmental diagnoses. The three groups showed no significant differences in age or nonverbal IQ (see Table 3 for an overview of IQ scores). Ethical approvals for this collaborative study were granted by Boston Children's Hospital, the Institute of Education at University College London, and the Edinburgh College of Art at the University of Edinburgh. All participants provided written informed consent.

-- Insert Table 1 --

Literacy Measures

Participants were characterized by a battery of standardized assessments that evaluated language and literacy abilities. Phonological awareness skills were assessed through the Elision and Blending subtests of the Comprehensive Test of Phonological Processing (CTOPP; (Wagner, Torgesen, & Rashotte, 1999)). Rapid automatized naming skills were measured through the Rapid Digit Naming and Rapid Letter Naming subtests of the CTOPP. Composite standard scores for phonological awareness and rapid naming were calculated. Phonological working memory was measured through composite score on

Digit Backwards and Digit Forward subtests of the Digit Memory Test (Turner & Ridsdale, 2004). Word reading and spelling were evaluated through the Wide Range Achievement Test (WRAT; (Wilkinson, 1993; Wilkinson & Robertson, 2006). Rapid (timed) single word reading was assessed through subtests of the Test of Word Reading Efficiency (TOWRE; (Torgesen, Wagner, & Rashotte, 1999)): Sight Word Efficiency (timed single-word reading) and Phonemic Decoding (timed decoding of non-words). Verbal and Nonverbal IQ were determined by the mean standard score of the two verbal subtests (Verbal Analogies/Similarities and Vocabulary) and two nonverbal subtests (Diamonds and Matrices) of the Wide Range Intelligence Test (WRIT; (Glutting, Adams, & Sheslow, 2000)) or equivalents from the Wechsler Adult Intelligence Scale (WAIS-III^{UK}; Wechsler, 1998). The WAIS and WRIT are strongly correlated and are therefore reported interchangeably (DfES, 2005). Inclusion criteria for participation in this study required a standard score of no less than one standard deviation below the mean (>85) on any of the IQ subtests. All participants in the TYPMUS group achieved scores within and above the average range on all measures of phonological processing, reading, and spelling (i.e., standard scores > 90).

In addition to a formal diagnosis of dyslexia, inclusion criteria were set based on reading and spelling achievement to validate the accuracy of self-reported diagnosis and ensure that a representative sample of individuals with dyslexia has been included in the DYSMUS and DYSNonMUS groups relative to the general population of adults with dyslexia (McLoughlin et al., 2002). Specifically, participants with dyslexia met the criteria for this study if they obtained a standardized score below 90 on at least one of the TOWRE subtests (Sight Word Efficiency or Phonemic Decoding). Accordingly, additional participants with dyslexia were excluded from analysis due to high scores on reading measures. In the case that participants with dyslexia provided the research team with a full diagnostic report that had been conducted within four years of study participation, standardized scores from measures that would have been re-administered in the present research study were taken from the diagnostic report. Thus, 52 participants as described above were included in the present analysis (TYPMUS $n = 17$; DYSMUS $n = 19$; DYSNonMUS $n = 16$).

Tone Sequencing Task

Tone sequences comprised of two complex tones with fundamental frequencies of 100 (low pitch) and 300 Hz (high pitch) in a modification of Tallal's Repetition Test (Tallal & Piercy, 1973). Both tones included eight harmonics with a six-decibel drop off, were equalized for power using a root-mean-squared formula, and had durations of 50, 75 and 125 ms. Tones were presented with different inter-stimulus intervals (ISIs) of 5, 10, 20, 40, 80 or 160 ms. For any given trial, all tones were of the same duration (50, 75, or 125 ms) and the ISI was constant (either 5, 10, 20, 40, 80 or 160 ms).

The tone sequencing task required participants to make a motor response (via button press) to indicate the order in which they heard the low- and high-pitched tones in each trial. The task began with training the motor response to each tone presented separately before progressing to replication of tone sequences of increasing length (two-, three- and four-tone sequences). Accuracy was measured by correct indication of low- and high-pitched tones in the same order as presented in each trial (any error within the sequence resulted in a score of zero for the trial). Reaction time for each trial was also acquired in all participants.

Syllable Task Stimuli

The syllable task comprised of the following three synthetic speech syllable continua: /ba-/da/ (spectral change within formant transition), /ba-/wa/ (duration change of formant transition/amplitude envelope), and /ga-/ka/ (change in Voice Onset Time; see Figure 1). The /ba-/da/ contrast was defined by direct changes in the onset of the second formant with a constant duration of the formant transition (40 ms) for all stimuli in the continuum. The /ba-/wa/ continuum involved manipulation of the amplitude envelope (as described in (Zuk et al., 2013b)), while the /ga-/ka/ continuum was created by altering the Voice Onset Time (VOT), both primarily involving a temporal change. Syllable stimuli were created through a Klatt-based synthesizer (Klatt, 1980). All syllables were 250 ms in duration and had a fundamental frequency (F0) of 120 Hz, which dropped to 90 Hz through the duration of the syllable. The specifications of the acoustic parameters used to synthesize the three continua were the following:

/ba-/da/ continuum: The onset value of the second formant for the /ba-/da/ continuum varied from 800 to 1600 Hz, (/ba/ and /da/, respectively), in 32 Hz steps producing 26 syllables spanning a

spectral continuum between /ba/ and /da/. The starting frequencies for the formant transitions of the /ba/-/da/ continuum were: F1 = 420 Hz, F2: varying from 800 to 1600 Hz, F3=2500 Hz, F4=3250 Hz, and F5=3700 Hz. The transition was 40 ms, at which point the formant frequency (F) and bandwidth (BW) values were: F1 = 800 Hz, BW1 = 90; F2=1200 Hz, BW2=110; F3=2500 Hz, BW3=90; F4=3250 Hz, BW4=400; F5=3700 Hz, BW5=500. At 180 ms, the formant frequency changes were: F1 = 750 Hz and the voicing was ramped down to zero for the remaining duration.

/ba/-/wa/ continuum: The duration of the transition varied from 25 to 97 ms (/ba/ and /wa/, respectively), in steps increasing by three milliseconds each, producing 25 syllables along this continuum. The frequency and bandwidth specifications were identical to the /ba/ used in the /ba/-/da/ continuum (see above) except F2 remained 800 Hz and the transition duration varied from 25 to 106 ms. This continuum has also been characterized by changes in the amplitude rise time duration, as previously analyzed by Zuk, Ozernov-Palchik and colleagues (2013).

/ga/-/ka/ continuum: The Voice Onset Time (VOT) for each syllable in the /ga/-/ka/ spectrum ranged from 10 to 60 ms, (/ga/ and /ka/, respectively) in two millisecond steps producing 26 syllables along this continuum. The starting frequencies for the formant transitions were: F1 = 300 Hz, F2 = 1625 Hz, F3 = 2000 Hz, F4 = 3250 Hz, and F5 = 3700 Hz. The formant frequency and bandwidth values at the beginning of the vowel were: F1=700 Hz, BW1=90; F2=1200 Hz, BW2=90; F3=2300 Hz, BW3=130; F4=3300 Hz, BW4=400; F5=3700Hz, BW5=500. At 180ms, the formant frequency changes were: F1 = 750 Hz, F2 = 1000 Hz, F3 = 2300 Hz and the voicing was ramped down to zero for the remaining duration.

-- Insert Figure 1 --

Participants were presented with a pair of syllables (one after the other with an inter-stimulus interval of 750 ms) and asked to indicate whether the two syllables sounded the same or different via button press. Each pair contained a fixed reference syllable (/ba/, /ba/, or /ga/ depending on the continuum) and a test syllable. The presentation order of the reference and test syllable was randomized throughout the task. The task progressed through trials in accordance with the three-down one-up

adaptive staircase method (Lakshminarayanan & Tallal, 2007). At the onset of the task, the test syllable was at the opposite end of the continuum from the reference syllable; that is, trials always began with the most easily discriminable stimulus pair from the continuum. Specifically, the discrimination limen of the first stimulus pair in the /ba-/da/ continuum corresponded to the syllable with a second formant frequency of 800 Hz (/ba/) and 1600 Hz (/da/), marking the extremes of the continuum. Accordingly, the discrimination limen of the first pair for the /ba-/wa/ continuum was 97 ms and for the /ga-/ka/ continuum, 60 ms.

After three consecutive correct responses to the first syllable pair, the discrimination limen decreased by two steps and the trials progressed accordingly. For each incorrect response, the discrimination limen increased by one step and an easier stimulus pair in the continuum was presented until seven reversals in the direction of progression of trials were achieved. Catch trials containing pairs of identical syllables were presented every 5–10 trials (for which all participants performed at 100%). Each assessment was terminated after seven reversals or five consecutive incorrect responses to the initial, most easily distinguishable pair. The discrimination thresholds for each of the stimulus continua were determined by the arithmetic mean of the discrimination limen corresponding to the last four reversals. The original threshold value was measured in Hz for /ba-/da/ and in ms for /ba-/wa/ and /ga-/ka/. Prior to commencing the task, participants completed a practice session of five syllable pairs to familiarize themselves with the stimuli and ensure they understood the instructions. In order to allow for direct comparison between the three syllable continua, the discrimination thresholds in Hz and ms were transformed into a Relative Threshold Index (RTI) ranging from zero to one (as previously described in (Zuk et al., 2013b); see Table 2 for conversion formulas).

Specifically, the RTI was the value obtained by subtracting the reference syllable value (for /ba-/da/ 800 Hz, for /ba-/wa/ 25 ms and for /ga-/ka/ 10 ms) from the obtained discrimination threshold. This number was then divided by the maximum range for each acoustic continuum (for /ba-/da/ 800 Hz, for /ba-/wa/ 97 ms and for /ga-/ka/ 60 ms) and subtracted from 1 (see Table 2). Thus, a higher RTI indicates better discrimination. For example, a discrimination threshold of 1400 Hz for the /ba-/da/

continuum would equate to an RTI of 0.25, while a discrimination threshold of 1000 Hz would be designated by an RTI of 0.75.

-- Insert Table 2 --

General Procedure and Analysis

For both experiments, participants were seated comfortably in a quiet testing room with a PC computer running ePrime (Psychology Software Tools, 2002). Stimuli were transmitted through Panasonic and Beyer stereo headphones. Comparisons between groups on language and literacy measures, the tone sequence task and syllable task performance were evaluated through one-way ANOVAs, repeated measures ANOVAs and post-hoc Games-Howell calculations. A priori, a sample size of at least 50 participants was estimated to be necessary to achieve at least 80% power with a large effect size (i.e., ≥ 0.4 based on standard effect size conventions for ANOVAs (Cohen, 1988) and the effect sizes of related previous studies), and an alpha-level threshold of 0.05 for ANOVA analyses with three groups and post-hoc group comparisons. Therefore, our sample size of 52 participants was deemed suitable to estimate group differences with sufficient power. In addition, post-hoc effect sizes were calculated to ensure that the expected effect sizes have been achieved. Specifically, effect sizes were estimated based on standard formulas for eta squared (η^2) from ANOVA analyses (Rosenthal & Rosnow, 1985, 1991), and the effect size index d as defined by Cohen for post-hoc comparisons of mean differences between groups (Cohen, 1969). Participants included in the present analysis completed administration of all three syllable contrasts; participants who were only administered one-to-two syllable contrasts due to time constraints were not included in the present analysis.

Results

Literacy Demographics

One-way ANOVAs investigating group differences on literacy-related measures revealed significant group differences for all measures of phonological processing, reading, and spelling (all significant at $p < 0.001$; see Table 3 for F-values corresponding to each specific measure). Post-hoc

Games-Howell tests for unequal variances showed that TYPMUS performed significantly better than both DYSMUS and DYSNonMUS on all measures (all significant at $p < 0.001$; see Table 3 for an overview) other than Nonverbal IQ, as expected given our inclusion criteria. Post-hoc direct comparison between DYSMUS and DYSNonMUS demonstrated that DYSMUS achieved significantly higher scores on the Sight Word Efficiency subtest than DYSNonMUS with a large effect size (Mean Difference (MD) = 6.984, Standard Error (SE) = 2.4, $p = 0.017$, $d = 0.981$), and these groups otherwise did not significantly differ on any other measures.

-- Insert Table 3 --

Tone Sequencing Task

For accuracy on the tone sequencing task, a repeated measures ANOVA (with group as the between-participant factor and the number of tones in the sequence as the within-participant factor) was implemented. First, inclusion criteria were established to ensure appropriate completion of the task, and that the participants had understood the task correctly. All participants achieved nearly 100% accuracy on all the single tone trials, indicating that they had no difficulty discriminating the pitch of the tones and understood the required key press response. Five DYSNonMUS did not complete this task due to time constraints during data collection (i.e., this task thus included the following number of participants in each group: TYPMUS: $n = 16$; DYSMUS: $n = 19$; DYSNonMUS: $n = 11$).

An ANOVA with repeated measures revealed significant differences in accuracy between groups with a large effect size ($F(2,43) = 65.821$, $p < 0.001$, $\eta^2 = 0.754$). Post-hoc Games-Howell tests revealed that TYPMUS and DYSMUS performed comparably (MD = 0.04, SE = 0.026, $p = 0.268$, $d = 0.454$), and both musician groups were significantly more accurate than DYSNonMUS for all tone sequences (all comparisons resulting in $p < 0.001$, $d > 0.4$). As shown in Figure 2, participants in all groups were significantly less accurate as the number of tones in each sequence increased ($F(2,42) = 136.762$, $p < 0.001$, $\eta^2 = 0.867$). Within each tone sequence, differences between the TYPMUS and DYSMUS groups relative to DYSNonMUS decreased as the inter-stimulus interval (ISI) increased for the two-tone and three-tone sequences, however, performance steadily increased in all three groups as ISI increased for the

four-tone sequence. Despite distinct patterns of differences in performance between groups as tone sequence and ISI increased, one-way ANOVAs and post-hoc Games-Howell tests revealed significant differences between DYSNonMUS and the TYPMUS and DYSMUS groups for all ISIs at each tone sequence (all comparisons resulting in $p < 0.001$, $d > 0.4$). Ceiling effects were observed within both TYPMUS and DYSMUS for all ISIs of the two-tone sequences and at an ISI of 80 and 160 ms for the three-tone sequence (see Figure 2). All groups performed above chance on average for each tone sequence (as indicated in Figure 2).

Reaction time on the tone sequence task was also found to significantly differ between groups, as revealed by ANOVA with a medium effect size ($F(2,43) = 70.182$, $p < 0.001$, $\eta^2 = 0.336$). Post-hoc Games-Howell tests revealed that TYPMUS and DYSMUS showed no significant differences in reaction time ($MD = 28.489$ msec, $SE = 21.862$ msec, $p = 0.395$, $d = 0.08$), albeit with a small effect size, whereas both TYPMUS and DYSMUS had significantly faster reaction times than DYSNonMUS on all tone sequences with large effect sizes (all comparisons resulting in $p < 0.001$, $d > 0.8$). As expected, reaction time significantly increased as the number of tones in each sequence increased for all three groups with a large effect size ($F(2,42) = 661.346$, $p < 0.001$, $\eta^2 = 0.827$).

-- Insert Figure 2 --

Syllable Task

Relative Threshold Index (RTI) outcomes for the three syllable continua were evaluated through ANOVA with repeated measures. Despite sufficient performance on practice trials immediately prior to commencing the task, ten participants with dyslexia (five DYSMUS, five DYSNonMUS) were unable to move forward on certain syllable continua beyond the first discrimination limen. After five consecutive incorrect responses to the initial, most easily distinguishable pair the task terminated. Consequently, these participants were assigned the first step in the continuum as their discrimination threshold and given an RTI score of zero for that particular syllable continuum. Instances of termination occurred in ten participants within specific syllable continua as follows: three for the /ba/-/da/ continuum, two for /ba/-

/wa/, and eight for the /ga/-/ka/ continuum (two of which also did not achieve beyond the first pair for /ba/-/da/, and one who was also terminated on /ba/-/wa/).

A series of ANOVAs confirmed significant between-subject group differences on all three of the syllable continua (see Table 4 for an overview). Direct group comparisons with post-hoc Games-Howell tests confirmed that for the /ba/-/da/ continuum, RTI scores did not significantly differ between TYPMUS and DYSMUS ($MD = 0.024$, $SE = 0.024$, $p = 0.595$, $d = 0.33$), and these two groups demonstrated superior discrimination thresholds than DYSNonMUS with large effect sizes (comparisons resulted in $p < 0.05$, $d > 0.8$). Similar group differences were found for the /ga/-/ka/ continuum varying in Voice Onset Time (VOT), in which post-hoc evaluation revealed no significant differences in discrimination thresholds between TYPMUS and DYSMUS ($MD = 0.062$, $SE = 0.076$, $p = 0.699$, $d = 0.27$). Although a relatively small effect size was found when comparing TYPMUS and DYSMUS, large effect sizes resulted from other group comparisons, in which TYPMUS demonstrated significantly better discrimination thresholds than DYSNonMUS for /ga/-/ka/ ($MD = 0.229$, $SE = 0.07$, $p = 0.007$, $d = 1.14$), and differences between DYSMUS and DYSNonMUS trended towards significance ($MD = 0.167$, $SE = 0.07$, $p = 0.056$, $d = 0.81$). Lastly, TYPMUS only showed heightened discrimination thresholds over DYSMUS for the continuum varying in amplitude envelope, /ba/-/wa/ ($MD = 0.219$, $SE = 0.07$, $p = 0.013$, $d = 1.03$), who in turn did not significantly differ from DYSNonMUS ($MD = 0.08$, $SE = 0.093$, $p = 0.699$, $d = 0.3$). An overview of group differences on each of these syllable continua is provided in Figure 3.

-- Insert Figure 3 & Table 4 --

Discussion

The present investigation of auditory sequencing and speech processing abilities in adult musicians with dyslexia who evidenced persistent literacy difficulties has revealed a distinct profile of abilities relative to both nonmusicians with dyslexia and typical musicians. As expected, typical musicians performed significantly better than musicians and nonmusicians with dyslexia on all literacy-related tasks and exhibited significantly better verbal intelligence scores, though all groups demonstrated

above average mean scores on this measure. Musicians and nonmusicians with dyslexia did not significantly differ on these standardized measures except for the sight word reading efficiency subtest, in which musicians with dyslexia showed better performance than nonmusicians with dyslexia. Characterization of tone sequencing abilities revealed, as expected, that the accuracy of musicians with dyslexia did not significantly differ from typical musicians, whereas nonmusicians with dyslexia performed significantly more poorly than both musician groups for all tone sequences and inter-stimulus intervals. As for the speech-specific perceptual tasks, which measured the discrimination thresholds of synthetic speech syllable continua, musicians with dyslexia did not differ from typical musicians for discrimination of two out of three acoustic properties isolated within the syllable continua. Specifically, musicians with dyslexia achieved discrimination thresholds that did not significantly differ from those of typical musicians on measures distinguishing spectral and VOT cues within syllables. Both musician groups also achieved significantly better discrimination thresholds than nonmusicians with dyslexia for these tasks. Yet, musicians with dyslexia did not differ from nonmusicians with dyslexia for discrimination of the /ba/-/wa/ contrast, which specifically evaluated the discrimination of amplitude envelope cues. With predominantly medium to large effect sizes corresponding to the present findings, it is evident that musicians with dyslexia showed advantages in auditory sequencing compared to nonmusicians with dyslexia. Musicians with dyslexia also showed refined speech discrimination abilities for two critical acoustic features, but demonstrated relative difficulties with discrimination of syllables varying by amplitude envelope.

The present findings suggest that musical training is associated with specialized auditory sequencing abilities in those with dyslexia, despite findings of poor auditory working memory performance in musicians with dyslexia. These results support our hypothesis that despite reading difficulties, musicians with dyslexia exhibit tone sequencing skills similar to those that have been shown to be developed and mastered in typical musicians (Carey et al., 2015; Loui et al., 2010; Rohrmeier et al., 2011; van Zuijen et al., 2005). These refined tone sequencing abilities in musicians with dyslexia are also in line with prior findings of auditory perception skills that did not significantly differ between musicians

with dyslexia and typical musicians for non-linguistic auditory tasks (Bishop-Liebler et al., 2014; Weiss et al., 2014). Conversely, nonmusicians with dyslexia demonstrated poor tone sequencing skills relative to musician groups, which is in line with previous reports of non-linguistic auditory processing deficits in individuals with dyslexia (Christmann et al., 2015; Grube et al., 2014; Marshall et al., 2001; Nitttrouer, 1999; Ramus, 2003; Rosen, 2003; Steinbrink et al., 2014a).

Although promising findings emerge from the tone-sequencing task, two significant considerations are important to note. First, a ceiling effect was observed in both musician groups for the two- and three-tone sequences, which makes it unclear whether a more complex non-speech task may further distinguish typical musicians relative to musicians with dyslexia. The second consideration concerns the validity of this task in measuring specifically auditory processing, and to what extent working memory may be taxed as the number of tones in each sequence increases. This should be taken into account, as prior studies have found auditory processing deficits to be concomitant with working memory difficulties (Ahissar et al., 2000; Banai & Ahissar, 2004). In the present sample, working memory, as measured behaviorally by the digit span test, revealed that typical musicians were superior to both groups with dyslexia, and musicians with dyslexia did not significantly differ from nonmusicians with dyslexia in digit span achievement, consistent with prior findings (Weiss et al., 2014). Therefore, despite working memory weaknesses relative to typical musicians, musicians with dyslexia demonstrated strengths in the present tone sequencing task. This finding is in line with the notion put forth by Weiss and colleagues (2014) that musicians with dyslexia seem to demonstrate divergent auditory processing skills, in which perception of auditory constituents in general present as a relative strength with significant weaknesses in auditory working memory.

As for speech-specific perceptual abilities in musicians with dyslexia, syllable discrimination thresholds significantly differed between musicians with dyslexia from both typical musicians and nonmusicians with dyslexia. For these tasks, it was hypothesized that a certain degree of specialization would be evident in musicians with dyslexia due to the considerable evidence that musical training is associated with refined speech processing abilities (Chandrasekaran & Kraus, 2010; Chobert et al., 2012;

Parbery-Clark et al., 2009; Patel, 2012; Tallal & Gaab, 2006). In support of this hypothesis, syllable discrimination did not significantly differ between musicians with dyslexia and typical musicians for discrimination of spectral cues (/ba/-/da/) and a temporal acoustic cue, voice onset time (VOT, as indicated by /ga/-/ka/). These findings align well with the growing evidence that trained musicians demonstrate specialized speech perception abilities in both spectral (Deguchi et al., 2012; Magne et al., 2006; Schon et al., 2004; Thompson et al., 2003) and temporal (Francois et al., 2012; Moreno et al., 2009; Zuk et al., 2013b) domains. Furthermore, these findings are in line with longitudinal studies that have shown enhanced neural responses in the auditory brainstem to speech stimuli following musical training (Kraus et al., 2014a; Kraus et al., 2014b, 2014c), suggesting that musical training may facilitate distinct mechanisms for speech processing.

For distinction of the /ba/-/da/ and /ga/-/ka/ contrasts, both musician groups were superior to nonmusicians with dyslexia. Poorer performance in nonmusicians with dyslexia was expected, since deficient speech sound representations have been found in individuals with dyslexia relative to controls for similar tasks involving discrimination of synthetic speech stimuli that varied in spectral and temporal features (Bogliotti et al., 2008; Manis et al., 1997). The present findings suggest that musical training may be a significant distinguishing factor when characterizing syllable discrimination abilities among individuals with dyslexia. Yet, it is important to also consider the subgroup of individuals with dyslexia, both with ($n = 5$) and without ($n = 5$) musical training, who were unable to reliably discriminate certain syllable continua in order to complete the task(s). The majority of these individuals exhibited difficulty with discrimination of the /ga/-/ka/ continuum which varied in temporal information ($n = 8$), though this difficulty was observed in all three syllable continua. This suggests a profound deficit in discriminating acoustic cues within syllable stimuli in approximately 28% of the adults with dyslexia in the present study regardless of musical training experience. This incidence (28%) is similar to previous reports of poor speech perception skills in dyslexia (Adlard & Hazan, 1998) and difficulty discriminating temporal cues (Overy et al., 2003). Taken together, the findings of this study support the notion that dyslexia is characterized by individual variability with regard to the severity of deficits in processing spectral and

temporal components of speech (Law et al., 2014; Liberman, 1985), even among those who have had musical training.

Although enhanced speech processing abilities were predicted in musicians with dyslexia, some weaknesses were also hypothesized for this group due to their persistent literacy difficulties. At the group level, weaknesses were found specifically for the distinction of amplitude envelope cues, a temporal feature critical to speech perception (Cutler, 1994; Rosen, 1992). Considerable evidence has been put forth for temporal processing deficits in individuals with dyslexia specific to perception of amplitude rise time and slow-rate modulations captured by the amplitude envelope (Goswami et al., 2002; Lorenzi et al., 2000; Rocheron et al., 2002; Talcott et al., 2000). This line of work has been further reflected by weaknesses in both musicians and nonmusicians with dyslexia in the detection of amplitude rise time cues within a non-linguistic context (Bishop-Liebler et al., 2014). Thus, relative to typical musicians, the observed weaknesses in discrimination of the /ba/-/wa/ contrast (characterized by changes in amplitude envelope cues) in the present sample of musicians with dyslexia as well as nonmusicians with dyslexia is in line with prior evidence. Despite the specialized speech perception abilities that these musicians with dyslexia exhibited for the other two syllable continua, discrimination of amplitude information within speech syllables proved to be an area of difficulty and may be associated with their persistent literacy difficulties.

While this study has found a distinct profile of auditory sequencing and speech processing abilities in musicians with dyslexia that is specialized relative to individuals with dyslexia who have not had musical training, a significant question remains: why do these individuals still have reading difficulties? Only individuals with persistent reading difficulties were recruited in the current study within the groups with dyslexia. Therefore, the musicians with dyslexia described presently are those whose reading difficulties have not been remediated over time despite long-term musical training. These persistent deficits are also evident in the literacy-related measures acquired within this study, as all participants with dyslexia obtained a standardized score below 90 on at least one of the reading tests and mean performance on all reading measures was within the low average range.

Thus, despite the specialized auditory sequencing and speech processing abilities found in musicians with dyslexia, these individuals do not show significantly better reading abilities than the nonmusical controls. Musicians and nonmusicians with dyslexia did not significantly differ on most of the literacy-related and working memory measures; musicians with dyslexia only achieved better scores than nonmusicians with dyslexia on the sight word reading efficiency subtest, which measures the ability to read familiar, well-known sight words as quickly as possible within one minute. This could point to possible compensatory strengths within these musicians with dyslexia. Nonetheless, it remains unclear whether these groups may differ in reading fluency or comprehension abilities, as these measures were not included in the present study design and should be explored in future research. Regardless, the source of persistent literacy difficulties among these adults with dyslexia remains unclear; whether it may be deficits in auditory working memory as suggested by Weiss and colleagues (2014) that were also found presently in both groups with dyslexia, or perhaps the observed difficulties in discrimination of syllables characterized by changes in amplitude envelope cues (i.e., the /ba/-/wa/ contrast). It is also possible that the perceptual difficulties observed in these individuals with persistent reading difficulties are due to a general underlying difficulty with perceptual anchoring, as suggested by Ahissar and colleagues (Ahissar et al., 2006; Oganian & Ahissar, 2012). In addition, the variance in performance on phonological and literacy measures among those with dyslexia in this sample supports the multidimensional view of dyslexia, which suggests a complex interplay between the factors that are associated with reading difficulties (Pennington, 2006). Furthermore, our findings suggest that non-literacy based experience, namely musical training, may also contribute to reading skill development. Overall, future longitudinal investigation is necessary to address these remaining unknowns and disentangle the extent to which musical training may directly modulate perceptual abilities, including whether it may serve to prevent persistent difficulties associated with dyslexia.

Taken together, this collective profile of auditory sequencing, speech processing, and literacy skills in musicians with dyslexia calls into question what the most significant contributing factors may be that have shaped these processing abilities in adulthood. Two longitudinal studies to date have

demonstrated literacy improvements following musical training in 8-11 year-old children with dyslexia, who received different types of musical training in each study (Flaugnacco et al., 2015; Habib et al., 2016). Although the evidence from the present study supports the potential of musical training to influence literacy outcomes, it remains unclear whether musical training directly supported the specialized auditory skills found in these adults since the present study did not employ a longitudinal design or capture these abilities during a developmental time period. Alternatively, since previous literature has demonstrated that not all individuals with dyslexia exhibit weaknesses in non-linguistic auditory processing (Hamalainen et al., 2013), it is possible that these musicians with dyslexia never had significant weaknesses in auditory processing, even from an early age. Based on the present study design, this study is unable to discern the answer to this question of whether these specialized processing abilities are a direct consequence of musical training or rather a propensity for success with musical training.

In addition, the present study is unable to address whether the persistence of dyslexia despite long-term musical training may point to the limitations of the benefit that musical training may offer in the literacy domain. This is particularly important to consider given the longitudinal evidence that literacy improvements following six weeks of computerized rhythm-based intervention in nine-year old children with dyslexia did not significantly differ from the improvements of controls who participated in phonics-based intervention or even passive controls who did not receive direct intervention (Thomson et al., 2013). Considering that those children were nine years old and that the average age of onset of musical training among the musicians with dyslexia in the present sample was seven years, this additionally calls into question whether musical training may have afforded more benefit if provided at an earlier age, concurrent with the period of rapid development of pre-literacy and literacy skills. In addition, the type and extent of musical training may be an important factor, as this computerized rhythm-based intervention did not lead to the same magnitude of effect as found in the study that implemented traditional musical training for two hours per week over 30 weeks (Flaugnacco et al., 2015). Another possibility could be that musical training concurrent with language and literacy-based intervention may lead to maximal benefits, such as the music-based intervention employed by Habib and colleagues that

directly integrated shared concepts between music and language to target dyslexia-specific goals (Habib et al., 2016). Thus, further research is needed within an earlier developmental time period to more fully assess the benefits of administering combined music and reading-related instruction/interventions on long-term literacy skill development and determine which approach may be the most effective.

Alternatively, it is possible there are factors that were not addressed directly within the present study that significantly contributed to these individuals' successes with musical training. These may include (but are not limited to) the following: first, participants' familial support and/or resources, such as remediation history or home literacy environment in childhood, given the high socioeconomic status overall of the present sample. Second, personal factors such as resilience or perseverance may also be significant traits among these musicians with dyslexia that have guided them to success with music, given the unique strengths that have been identified in some individuals with dyslexia (Davis, 2010). Third, it is also possible that these individuals have developed a compensatory strategy that is advantageous for auditory processing and distinct from others with dyslexia (i.e., those who have not had musical training). More detailed documentation of each individual's treatment history would have been valuable to determine the extent to which therapy experience supported the development of compensatory mechanisms, and how these experiences may relate to musical training status as well as non-speech and speech processing abilities. It is also important to note that although musicians and nonmusicians with dyslexia in this study did not differ in their average age of diagnosis, this average age was 17 years, which seems relatively late in development to receive a diagnosis. By implication, it seems likely that many of these individuals probably did not receive literacy-specific intervention during literacy onset in childhood, although they may have received general classroom support. This is conceivable given the present standard clinical diagnostic procedures in the UK (DfES, 2005), though it raises a question of whether and how these individuals with dyslexia managed their academics with minimal support services until college, and how age of diagnosis may relate to long-term language, literacy, and musical abilities. Lastly, the present sample was not large enough to evaluate whether specific attributes of the specialized non-speech and speech-specific processing among musicians in the present sample may be associated with the

type of instrument studied. This could be of interest to explore in the future, since instrument-specific effects have been proposed previously (Carey et al., 2015). For example, string instrumentalists have demonstrated particular specialization in the pitch domain (Koelsch et al., 1999), and percussion instrumentalists have been characterized by specific expertise in temporal features such as timing and rhythm (Patel, 2012). While the present study advances the extant evidence investigating auditory processing abilities in musicians with dyslexia, these considerations are to be addressed in future research pursuits.

In conclusion, the present study provides further specification of auditory sequencing and speech processing abilities that characterize musicians with dyslexia who show persistent reading difficulties. Musicians with dyslexia have demonstrated specialized processing abilities for auditory sequencing and multiple speech-specific contexts, for measures with no significant differences relative to typical musicians, and performed significantly more poorly than typical musicians only for the discrimination of syllables that varied in amplitude envelope cues. Our findings suggest that it is important to account for musical training in the investigation of auditory processing skills in individuals with dyslexia, for musical involvement may shape long-term auditory processing abilities. Furthermore, implications are evident for the potential of musical training to support specific aspects of auditory processing in individuals with dyslexia. However, more developmental and longitudinal studies are needed to determine whether these advantages are indeed a direct result of musical training as opposed to predispositions for success with music, whether there is a specific profile of abilities within those with dyslexia that will benefit most from musical training, and whether a combined music and literacy-based instruction/intervention may be the most effective approach. Nevertheless, this work suggests that it is important to maintain music programs within the grade school curriculum, and advocates for children with dyslexia to continue to participate in music in addition to direct evidence-based literacy support.

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Table 1

Overview of musical experience and type of instrument for TYPMUS and DYSMUS

| | TYPMUS | DYSMUS | Sig (p-value) |
|---------------------------------------|------------------|------------------|----------------------|
| | Mean \pm SD | Mean \pm SD | Two-tailed |
| <i>Musical Characteristics</i> | | | |
| Age began musical training | 7.25 \pm 2.67 | 7.35 \pm 3.12 | 0.92 |
| Years of musical training | 12.88 \pm 4.18 | 13.18 \pm 2.63 | 0.81 |
| <i>Type of Musical</i> | | | |
| <i>Instrument</i> | Number of Adults | Number of Adults | |
| Woodwinds | 3 | 5 | |
| String | 1 | 4 | |
| Brass | 0 | 3 | |
| Keyboard | 4 | 1 | |
| Percussion | 0 | 1 | |
| Voice | 9 | 5 | |

Table 2

Attributes of the syllable continua and calculation of the relative threshold index (RTI)

| Syllable Pair | Reference Syllable | Original Threshold | Relative Threshold Index |
|---------------|--------------------|--------------------|---|
| <hr/> | | | |
| /ba/-/da/ | | | |
| 800Hz | – /ba/ (800Hz) | x Hz | $1 - [x \text{ Hz} - 800 / (1600\text{Hz} - 800\text{Hz})]$ |
| 1600Hz | | | |
| <hr/> | | | |
| /ba/-/wa/ | | | |
| 25ms – 97ms | /ba/ (25ms) | x ms | $1 - [x \text{ ms} - 25 / (97\text{ms} - 25\text{ms})]$ |
| <hr/> | | | |
| /ga/-/ka/ | | | |
| 10ms – 60ms | /ga/ (10ms) | x ms | $1 - [x \text{ ms} - 10 / (60\text{ms} - 10\text{ms})]$ |
| <hr/> | | | |

Table 3

Group characteristics as outlined by standardized measures of phonological processing, reading, and spelling

| | | TYPMUS | DYSMUS | DYSNonMUS | F (max df = 2,49) |
|-------------------------------------|--------------|----------------|----------------|------------------|--------------------------|
| | | Mean ± SD | Mean ± SD | Mean ± SD | |
| <i>Group Characteristics</i> | | | | | |
| WRIT | Verbal IQ | 117.78 ± 11.78 | 110.11 ± 8.17 | 107.19 ± 12.07 | 5.08 ^{*a} |
| | Nonverbal IQ | 114.89 ± 7.23 | 113.45 ± 5.34 | 111.34 ± 6.54 | 1.19 |
| | Sight Word | | | | |
| TOWRE | Efficiency | 105.94 ± 8.44 | 87.42 ± 7.60 | 80.43 ± 6.62 | 50.23 ^{*b} |
| | Phonemic | | | | |
| | Decoding | 114.35 ± 6.78 | 87.52 ± 6.04 | 84.12 ± 8.81 | 89.30 ^{**c} |
| WRAT | Reading | 113.88 ± 6.41 | 99.36 ± 7.19 | 95 ± 7.28 | 33.76 ^{***c} |
| | Spelling | 113.47 ± 6.34 | 97 ± 7.13 | 97.18 ± 6.75 | 33.56 ^{***c} |
| | Digit Memory | 109.82 ± 14.24 | 89.47 ± 10.25 | 85.68 ± 11.93 | 19.21 ^{***c} |
| CTOPP | Elision | 107.06 ± 3.98 | 91.06 ± 12.98 | 87.18 ± 16.12 | 12.75 ^{***c} |
| | Blending | 115.59 ± 8.27 | 102.22 ± 13.97 | 95 ± 13.67 | 12.08 ^{***c} |
| | Phonological | | | | |
| | Awareness | | | | |
| | Composite | 113.59 ± 6.01 | 95.83 ± 12.78 | 90.125 ± 12.47 | 21.15 ^{***c} |
| | Rapid Digit | 110.29 ± 7.39 | 96.44 ± 13.82 | 87.81 ± 11.69 | 16.60 ^{***c} |

Naming

Rapid Letter

| | | | | |
|--------|----------------|---------------|---------------|-----------------------|
| Naming | 106.76 ± 11.45 | 87.72 ± 10.69 | 83.87 ± 11.84 | 19.75*** ^c |
|--------|----------------|---------------|---------------|-----------------------|

Rapid Naming

| | | | | |
|-----------|----------------|--------------|---------------|-----------------------|
| Composite | 110.24 ± 10.18 | 90.5 ± 13.81 | 82.94 ± 13.58 | 20.76*** ^c |
|-----------|----------------|--------------|---------------|-----------------------|

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

^aGames-Howell post-hoc tests on one-way ANOVA by group found that TYPMUS performed significantly better than DYSNonMUS; DYSMUS and DYSNonMUS did not significantly differ

^bGames-Howell post-hoc tests on one-way ANOVA by group found that TYPMUS performed significantly better than DYSMUS, who are in turn better than DYSNonMUS

^cGames-Howell post-hoc tests on one-way ANOVA by group found that TYPMUS performed significantly better than DYSMUS and DYSNonMUS; DYSMUS and DYSNonMUS did not significantly differ

Table 4

Discrimination thresholds for syllable continua by group as described by the Relative Threshold Index (RTI)

| | TYPMUS | DYSMUS | DYSNonMUS | F (max df = 2,49) |
|------------------|---------------|---------------|------------------|--------------------------|
| | RTI | RTI | RTI | |
| /ba/-/da/ | 0.43 | 0.41 | 0.26 | 9.20*** ^b |
| /ba/-/wa/ | 0.68 | 0.47 | 0.39 | 7.32*** ^a |
| /ga/-/ka/ | 0.37 | 0.31 | 0.14 | 5.01** ^b |

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

^aGames-Howell post-hoc tests on one-way ANOVA by group found that TYPMUS performed significantly better than DYSMUS and DYSNonMUS; DYSMUS and DYSNonMUS did not significantly differ

^bGames-Howell post-hoc tests on one-way ANOVA by group found that TYPMUS did not significantly differ from DYSMUS; both TYPMUS and DYSMUS were better than DYSNonMUS

Figure 1. Experimental Stimuli: The spectrograms show the end points of the three continua /ba/-/da/, /ba/-/wa/, /ga/-/ka/). The onset value of the second formant in the /ba/-/da/ continuum varied from 800–1600 Hz. The duration of the formant transition in the /ba/-/wa/ continuum varied from 25–97 ms. The Voice Onset Time (VOT) of the first formant in the /ga/-/ka/ continuum varied from 10–60 ms.

Figure 2. Performance accuracy on the tone sequence task displayed by group (open circles: TYPMUS, filled squares: DYSMUS, filled triangle: DYSNonMUS) for the two-, three-, and four-tone sequences. Gray lines indicate chance (2-tones, 0.25; 3-tones, 0.125; 4-tones, 0.0625).

Figure 3. Outcome for the three syllable continua on the syllable task. Mean Relative Threshold Indices (RTI) by group is displayed (dark gray: TYPMUS, light gray: DYSMUS, gray: DYSNonMUS) for each syllable continua; error bars indicate standard error. Higher RTI scores represent better discrimination. Significance indicated by $*p < 0.05$ and $**p < 0.01$ for post-hoc Games-Howell comparisons between groups.





